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Development of a GIS Tool for Rainfall-Runoff Estimation

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Abstract— ***The problem of transformation of rainfall to runoff has been a subject of scientific investigations and evaluation throughout the field of hydrology. A number of investigators have tried to relate runoff with various governing characteristics of watersheds such as the time of concentration. This work focuses on using Visual Basic for Application (VBA) programming language and Arc Objects advanced customization techniques constructed in a Geographic Information System (Arc-GIS) to develop a hydrologic new tool to predict surface runoff hydrographs for watersheds. The VBA applications were used to develop, use and present all data in a GIS toolbar including morphological parameters calculations. The new toolbar will facilitate assessing and predicting hydrographs through calculating the time of concentration and other morphological parameters with acceptable accuracy with respect to other manual approaches. The most attractive feature of this tool is its ability to automatically delineate and simulate any number of catchment areas simultaneously on digital elevation models.***

Keywords— ***Runoff, Hydrograph, Visual Basic, Arc-GIS, Model, Arc Object***

I. INTRODUCTION

The watershed hydrologic models have been developed for many different reasons and therefore have many different forms. Recently, mathematical models have taken over the most important tasks of problem solving in hydrology. The main aim of this study is to use the Geographic Information Systems (GIS) for improving the morphological analysis and morphological parameters estimation as an important pre-step to hydrological analysis. This will be achieved through the development of a user Geographic Information Systems (GIS) tool using Visual Basic for Application (VBA) in Arc Objects environment to develop, use and present all morphological analysis models and parameters estimation models in a GIS toolbar that could be later used to simulate the rainfall-runoff hydrograph.

Maidment (1996) suggested the use of raster-based GIS to derive a spatially distributed unit hydrograph (SDUH). His conceptual procedure can be summarized as follows: Starting with the digital elevation model (DEM) of the watershed, flow direction is determined from each cell to one of its eight neighbouring cells and is taken to be the direction of the maximum downhill slope. In his study a concept was used to provide a spatially distributed unit hydrograph (SDUH). This SDUH was applied to the study watershed using the Uniform Excess rainfall (U-Excess) model uses a single "average" CN for the whole watershed, thus generating a uniform excess rainfall. The results obtained by using the SDUH models was compared to those obtained using the observed hydrographs. Ajward and Muzik (2000) tried to include a discharge - dependent travel time calculations (based on hydraulics) and a spatially averaged curve number (CN). Chiang et al. (2004) tried to take the effect of rainfall intensity in travel time calculations based on a spatially varied Manning’s formula that relates the discharge at a grid point to the flow accumulation value (i.e., the number of accumulating upstream cells).

II. MODEL DEVELOPMENT

In order to meet the goals of this study, a spatially distributed unit was developed such that it only relied on Digital Elevation Model (DEM) data to calculate watershed characteristic and time of concentration as important information for rainfall-runoff model input.

To apply the model various raster datasets are required, including both basic raster files (basically DEM files) and others derived from the basic maps. The slope, flow direction, flow path, upstream area, and channel network raster are all derived from the DEM.

The ArcGIS software was used in this study. All calculations were made on raster based layers. Watershed topographic properties needed in this study were derived from a digital elevation model (DEM) with 90-m resolution. A VBA model was developed to present all data in a GIS toolbar. The developed toolbar is named HMS-ASUFE (Hydrologic Modelling System – Ain Shams University Faculty of Engineering). HMS-ASUFE tool bar will consists of 5 modules; terrain pre-processing module, basin module, hydrologic module, Meteorologic module and design flow module, figure 1. Each module is divided into sub modules, which consist of custom–programmed scripts and forms. This manuscript represents the development of the first three modules.

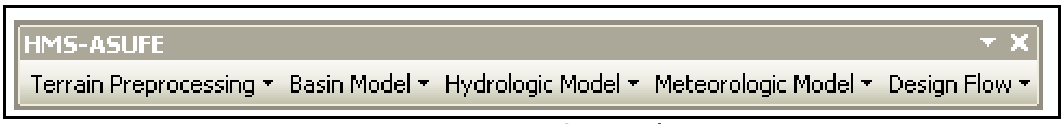

Fig. 1 HMS-ASUFE Tool Bar Interface

Terrain Pre-processing module consists of one sub-module entitled "***Delineate Catchment***". Delineate Catchment sub-module uses DEM to identify the surface drainage pattern. Once pre-processed, the DEM and its derivatives can be used for efficient watershed delineation, figure (2).

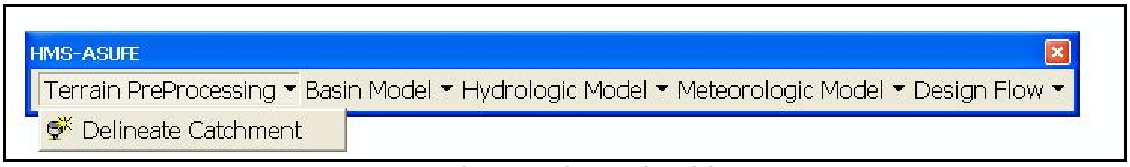

Fig. 2 Delineate Catchment Sub module

Figure (3) shows the model builder for delineate catchment.

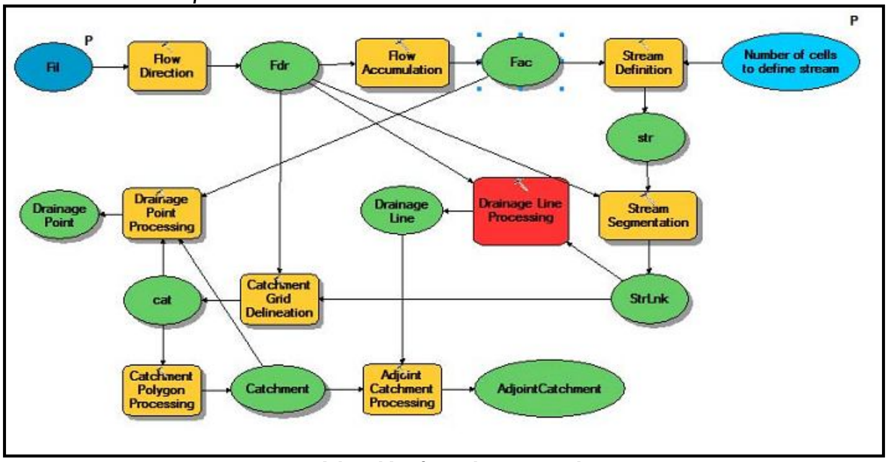

Fig. 3 Model Builder for Delineate Catchment

After clicking the "***Delineate Catchment***" button, a message box appears requires inserting the raw DEM and threshold area, in km^2, to define the stream in a watershed, figure (4).

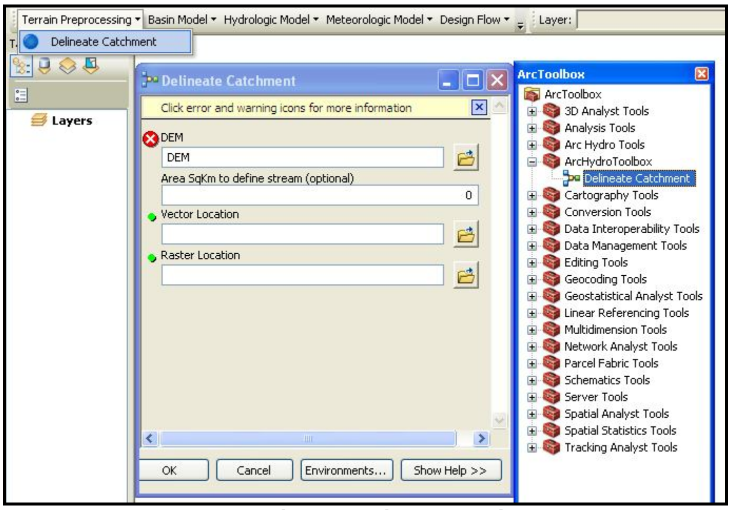

Fig. 4 Delineate Catchment Wizard

All the steps in the "***Delineate Catchment***" sub-module will then run automatically, these steps will be performed in automatic sequential order as follows in figure (5).

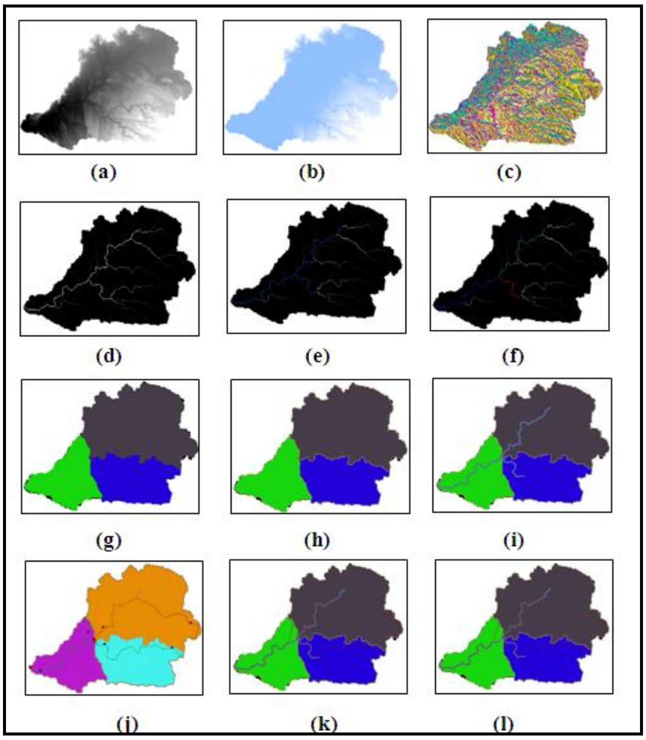

Fig. 5 Steps of the Automatic Delineation
(a) DEM Manipulation and Fill Sinks, (b) Flow Direction, (c) Flow Accumulation, (d) Stream Definition, (e) Stream Segmentation, (f) Catchment Grid Delineation, (g) Catchment Polygon Processing, (h) Drainage Line Processing, (i) Adjoint Catchment Processing, (j) Drainage point Processing, (k) Longest Flow path for Catchment, and (l) Longest Flow Path parameter from 2D.

Basin Model module consists of one sub-module entitled "***Generate Morphological Parameters***", figure (6).

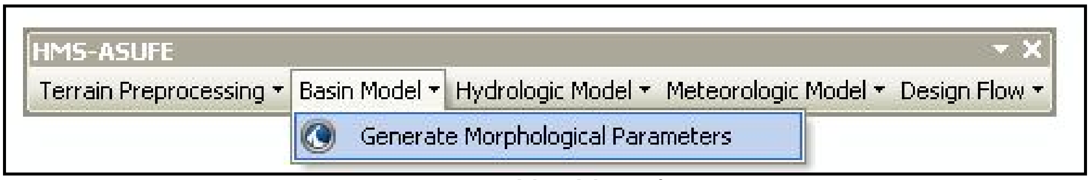

Fig. 6 Basin Model Module Interface

Generate Morphological Parameters sub-module generates new fields in the attribute table of the longest flow path layer to calculate automatically the morphological parameters of the catchments (area, and perimeter). As for the longest flow path, it will be divided into three reaches to represent and calculate its parameters more accurately. The characteristics of these reaches are L1, L2, L3, S1, S2, and S3, figure (7).

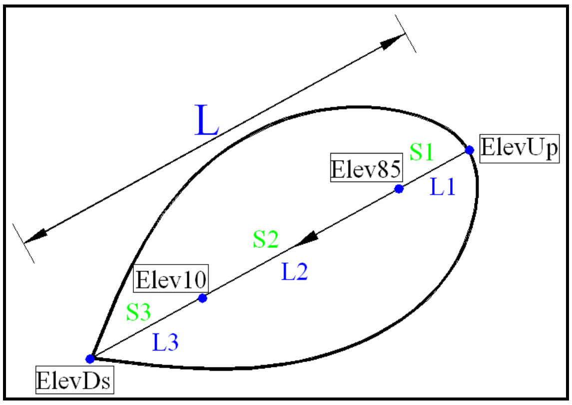

Figure (7) Longest Flow Path Divisions According to Length

The equations used to get these characteristics are as follows;

$$L1 = 0.15\ L \qquad [1]$$

$$L2 = 0.75\ L \qquad [2]$$

$$L3 = 0.10\ L \qquad [3]$$

$$S1 = \frac{ElevUp - Elev85}{L1} \qquad [4]$$

$$S2 = \frac{Elev85 - Elev10}{L2} \qquad [5]$$

$$S3 = \frac{Elev10 - ElevDs}{L3} \qquad [6]$$

Once pre-processed, these fields appear in the attribute table of the longest flow path layer as shown in figure (8).

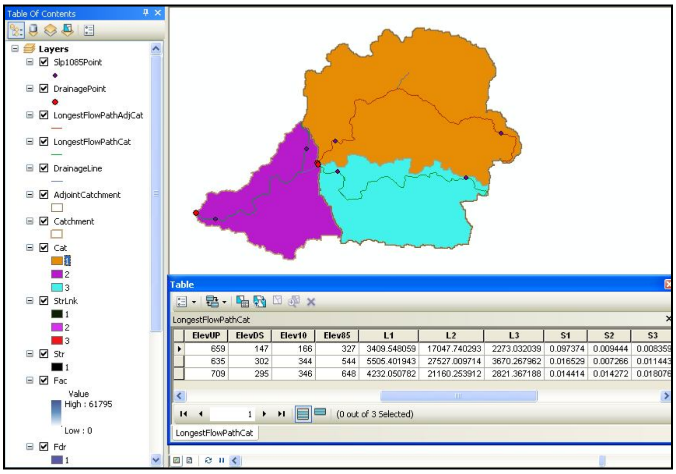

Fig. 8 Basin Model Module after Execution

Hydrologic Model module consists of one sub module with name "***Generate Hydrologic Parameters***", figure (9).

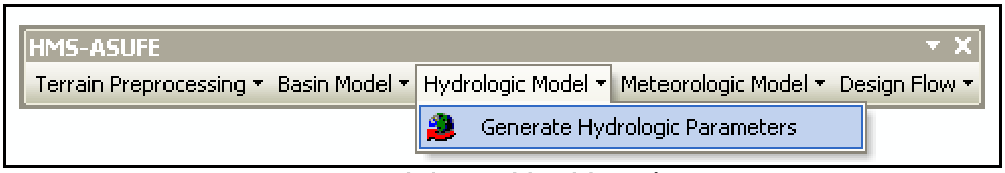

Fig. 9 Hydrologic Model Module Interface

Generate Hydrologic Parameters sub module generates new fields in the attribute table of the longest flow path layer to calculate automatically the hydrological parameters (those used in rainfall-runoff modules). The longest flow path will be divided into three reaches as previous step exactly to get high accuracy for hydrological parameters calculations. The characteristics of these reaches are T_{c1}, T_{c2}, T_{c3}, Tc, T_L , figure (10).

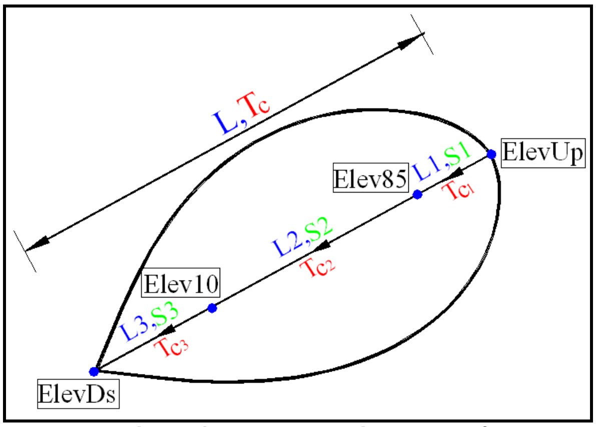

Fig. 10 Longest Flow Path Divisions According to Time of Concentration

The equations used to get these characteristics are as follows;

$$T_{c1} = a \times L_1^b \times S_1^c \times A^d \quad [7]$$

$$T_{c2} = a \times L_2^b \times S_2^c \times A^d \quad [8]$$

$$T_{c3} = a \times L_3^b \times S_3^c \times A^d \quad [9]$$

$$T_c = T_{c1} + T_{c2} + T_{c3} \quad [10]$$

$$T_L = 0.6\, T_c \quad [11]$$

Where T_c = Time of concentration, T_L = Lag time (based on the SCS assumption), A = Area of the catchment, and a, b, c, and d are factors depending on the method used for time of concentration calculation and should be entered by the user once the module has been activated. Once pre-processed, these fields appear in the attribute table of the longest flow path layer, figure (11).

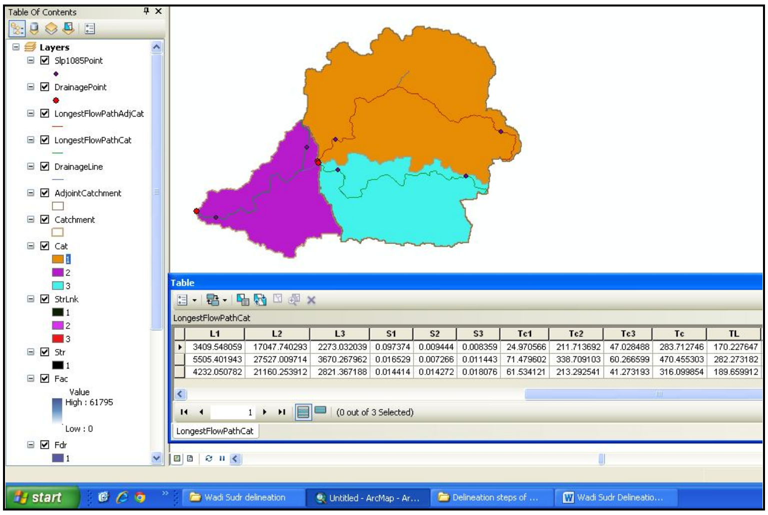

Fig. 11 Hydrologic Model after Execution

Meteorological Model module consists of two sub modules "SCS Storm and Depth (mm)", figure (12). The 1st SCS Storm sub module allows selecting the design storm from the four types of SCS storms (Type I, Type IA, Type II, and Type III) as default rainfall distribution. The 2nd depth (mm) sub module allows entering the daily rainfall depth of the design storm to be distributed as per the storm type selected.

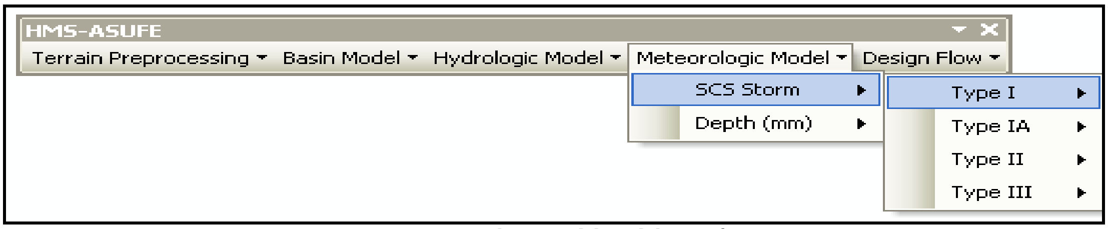

Fig. 12 Meteorologic Model Module Interface

The time step used in the model equals to 1 minute that will be used during the rainfall–runoff calculations.

Design Flow module consists of four sub modules, figure (13). Each sub module consists of three sub modules "Import Parameters, Output Hydrograph, and Output Time Series". The Import Parameters sub module allows importing CN, and the area of the studied sub basin from the attribute table, the Output Hydrograph sub module allows displaying the output hydrograph of the studied sub basin, and the Output Time Series shows the time series of the output hydrograph in a tabulated form.

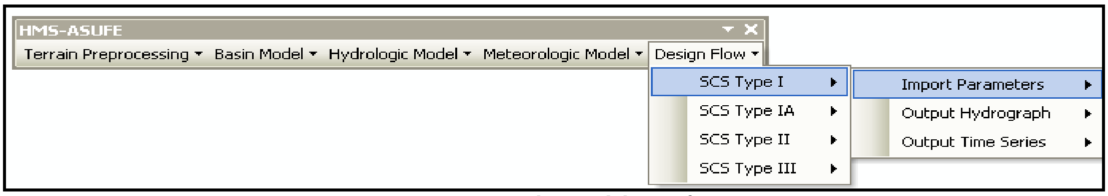

Fig. 13 Design Flow Module Interface

A calculation matrix was programmed to convert the effective rainfall to direct runoff to get the output hydrograph for based on the UH concept.

$Q_n = \sum P_i U_{n-i+1}$ (1<n<m+M-1) [12]

$Q_0 = Q_n = 0$ for (n>m+M-1) [13]

Where;

m is the duration of the effective rainfall

M is the time base of the unit hydrograph

U is the unit hydrograph developed based on the SCS assumptions.

This could be presented in a matrix form as follows; Q = PU

$$P = \begin{bmatrix} P_1 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ P_2 & P_1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ P_3 & P_2 & P_1 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & & & & \vdots & & & & \vdots \\ P_m & P_{m-1} & P_{m-2} & \cdots & P_1 & 0 & \cdots & 0 & 0 \quad 0 \\ 0 & P_m & P_{m-1} & \cdots & P_2 & P_1 & \cdots & 0 & 0 \\ \vdots & & & & \vdots & & & & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & P_m & P_{m-1} \\ 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & P_m \end{bmatrix}$$

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ \vdots \\ U_{M-1} \end{bmatrix} \qquad Q = \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ \vdots \\ Q_{m+M-2} \end{bmatrix}$$

III. Model Testing

The HMS-ASUFE model was tested on a watershed in Sinai “Wadi Sudr”, figure 14 and compared its results with the output hydrograph of the HEC-HMS model of the US Corps of engineers.

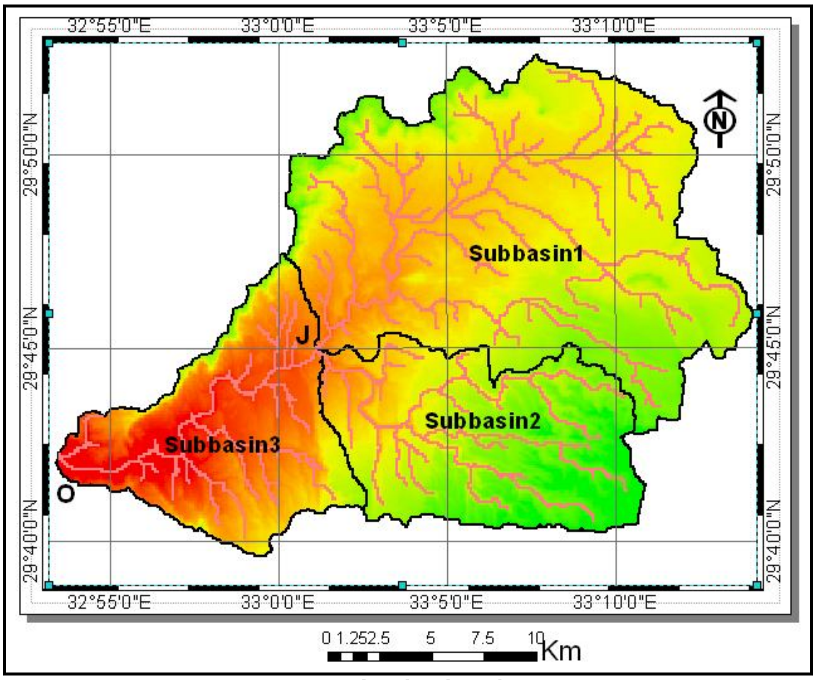

Fig. 14 Wadi Sudr Sub catchments

Results were also compared to the observed flow hydrograph. Both visual and statistical comparison between different model hydrographs and observed flows were made, figure 15.

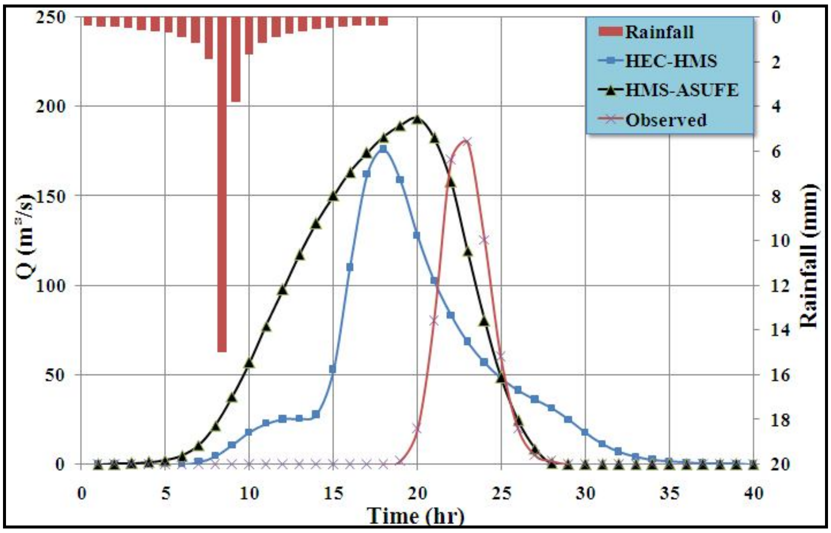

Fig. 15 Runoff Hydrographs and Rainfall at Outlet Using HEC-HMS, HMS-ASUFE by SCS Type 2, and Observed Hydrograph

	Peak Discharge (m^3/s)		
Junction & Outlet	**HEC-HMS**	**HMS-ASUFE**	**Observed**
Junction (J)	165	175	----
Outlet (O)	175	190	180

The results for both HEC-HMS and HMS-ASUFE were better matching without applying the routing effect through the reach between the junction and the catchment outlet. The lag time routing method was used in the model, the difference between the two models was only 6.1% at the junction while increased to 8.5% at the outlet. Yet both models is having an error ranging between (2.78 to 5.56 %) when compared with the observed flow.

IV. CONCLUSIONS

The main aim of (HMS-ASUFE) model is to develop a new GIS tool for hydrological system studies. The manuscript presented the development steps for the model using VBA. The menus and buttons of the developed model are controlled by VBA-scripts to present all data in a GIS toolbar and can be modified with user written scripts.

The run time of grid-based analysis depends mainly on the number of grid cells (i.e., grid dimensions: number of columns by number of rows). HMS-ASUFE run time is excellent for engineering applications. It takes seconds in small grids (areas up to 5000 km^2) using the typical SRTM resolution of 100 m (i.e., 5 x 105 cells).

This model, in addition to the fast run time and the ability to handle many catchment areas simultaneously, make HMS-ASUFE very suitable to real time applications on both the small and large scales. In addition, it is a feasible and efficient tool for hydrologists seeking accurate and quick morphological and hydrological parameters calculations especially when many catchment areas are considered. A general equation for time of concentration calculation was adopted in the model to make it applicable for wider range of design codes and standards. The resulted hydrographs for both HEC-HMS and HMS-ASUFE showed a close results yet further work is in progress to investigate the routing effect and implement different routing techniques to the new developed model.

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